

Battery Testing and Life Estimation in the US

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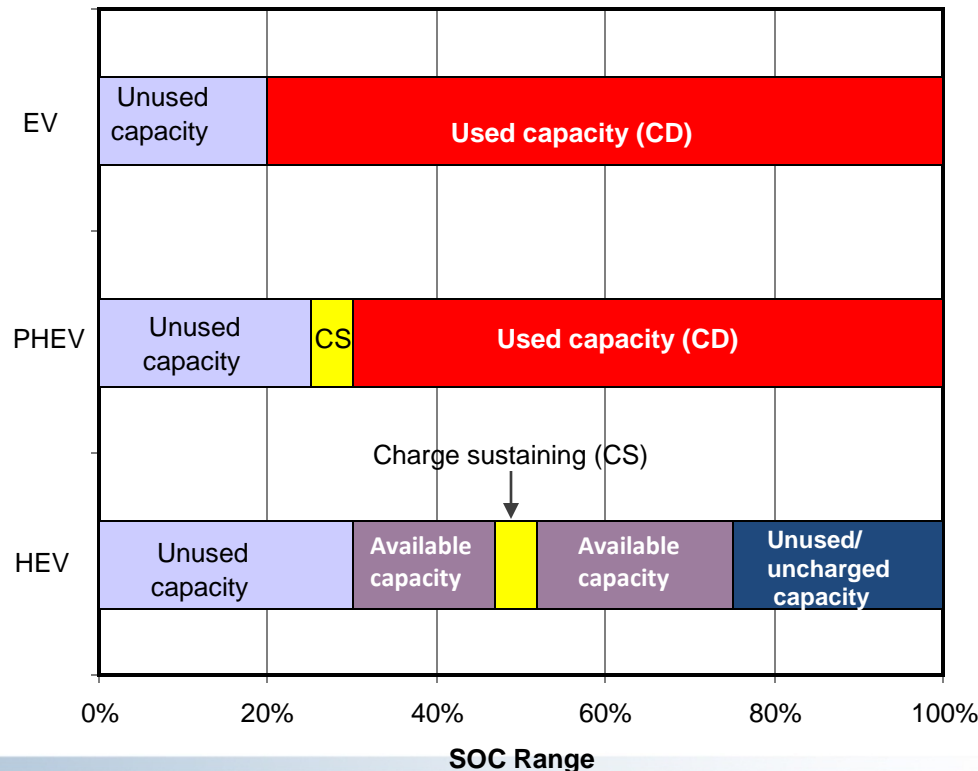
Battery Testing in the US

- Battery performance and life testing in the US is an application-driven, analytical process
- Current focus is on HEVs, PHEVs and EVs
- For simplicity, this presentation will be focused on test methods for PHEVs and EVs at the pre-competitive stage
- General testing philosophy
 - Obtain sufficient information in a limited amount of time to gauge the performance of a battery without exhausting it
 - The test procedures employ accelerated aging techniques
 - The test procedures used are applicable to cells, modules and complete battery systems
- Anatomy of battery testing
 - Characterize the performance of a battery
 - Age it under controlled conditions
 - Measure changes in performance by repeating portions of the characterization tests
 - A reference performance test



Vehicle Stress on Battery

- Each type of electric vehicle uses the capacity/energy of the battery differently
 - EV: use about 80% of available battery energy for vehicle propulsion (all electric range, AER)
 - PHEV: use about 70% for electric propulsion (high SOC, AER) and about 5% for hybrid operation (low SOC)
 - HEV: use about the central 50% of the battery for operation (charge sustaining)
- Thus, the battery has to be sized and engineered to accommodate demands from the vehicle



Vehicle Assumptions At Pre-competitive Stage

- Other considerations: vehicle mass, aerodynamic and rolling resistances, vehicle performance (top speed/acceleration), electric range, operating strategy and usable energy window
- Three vehicle types were selected to represent different energy requirements and to represent various sectors of the light-duty US vehicle market
 - Midsize car (ex: Chevy Malibu)
 - Midsize crossover utility vehicle (CUV, ex: Chrysler Pacifico)
 - Midsize sport utility vehicle (SUV, ex: Ford Explorer)

Parameter	Units	Midsize car	Midsize crossover UV	Midsize SUV
Approximate Vehicle mass	kg	1600	1950	2000
Frontal area	m ²	2.2	2.7	2.9
Drag coefficient		0.3	0.4	0.4
Rolling resistance		0.009	0.010	0.011
Accessory electrical load	W	800	1000	1200

Data from: Pesaran, Markel, Tataria and Howell, EVS23 Symposium, Anaheim, CA, December 2007



Vehicle Modeling Shows Energy/Power Requirements for PHEVs

- Urban Dynamometer Driving Schedule (UDDS) was used as basis for modeling the vehicles, with a minimum AER of 10 mi (16 km)
- Analysis of energy requirements showed:
 - Midsize car consumed about ~280 Wh/mi (~175 Wh/km)
 - Midsize CUV, ~340 Wh/mi (~210 Wh/km)
 - Midsize SUV, ~420 Wh/mi (~260 Wh/km)
- Analysis of power requirements showed (mid AER power, 2s):
 - Midsize car, 46 kW
 - Midsize CUV, 50 kW
 - Midsize SUV, 70 kW
- For a 10-s pulse, the power would be about 75% of these values
 - Midsize car, ~35 kW
 - Midsize CUV, ~37 kW
 - Midsize SUV, ~53 kW



Using These Results, Goals Were Established

- In the near-term (2012), batteries are expected to have high power:energy ratio, based on work with current hybrid electric vehicles; early market penetration
 - 10 mi AER vehicles
- In the longer-term (2015-16), higher energy batteries (lower power:energy ratio) are expected to become available
 - 40 mi AER vehicles
- A mid-term goal was also established, representing an intermediate stage of development
 - 20 mi AER vehicles
- The results were then generalized to be free of the specific vehicles mentioned earlier and are used in battery development
- It should also be noted that the starting SOC for the capacity/energy range that is used in the CD was left to the battery developer



PHEV Battery Testing

- The US Advanced Battery Consortium (USABC) has established performance and life targets for PHEVs
- Intended vehicle platforms
 - Minimum PHEV battery target: a sport utility vehicle with a mass of 2000 kg and with an equivalent electric range of 10 miles (16 km)
 - Medium PHEV battery target: a passenger car with a mass of 1600 kg and with an equivalent electric range of 20 miles (32 km)
 - Maximum PHEV battery target: a passenger car with a mass of 1500 kg and with an equivalent electric range of 40 miles (64 km)
- The goals are directly applicable to complete battery systems; most can be applied to the testing of modules, cells or sub-scale cells with appropriate scaling (battery scale factor)

Selected Energy Storage System Target Values

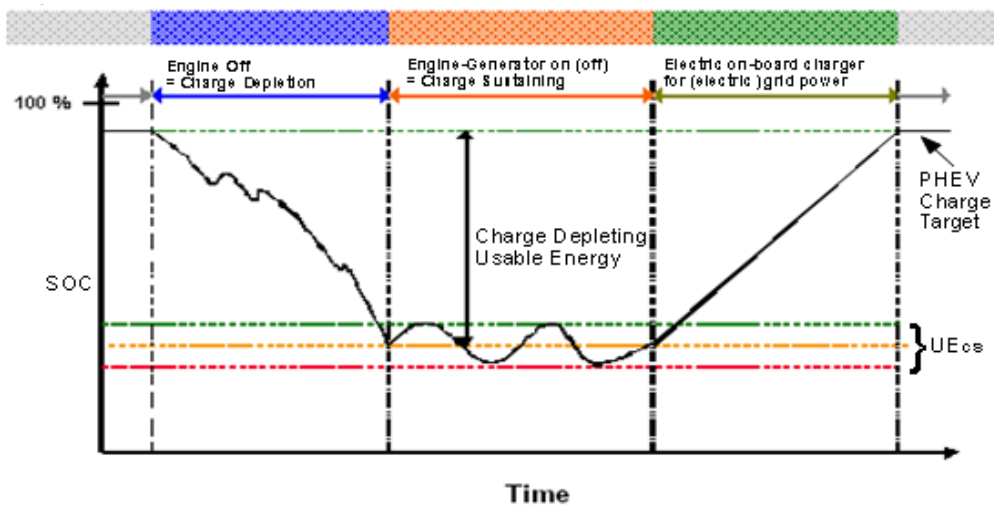
Characteristics at EOL (End-of-Life)	Unit	Min PHEV Battery	Med PHEV Battery	Max PHEV Battery
Equivalent Electric Range	Miles (km)	10 (16)	20 (32)	40 (64)
Peak Discharge Pulse Power (2 sec /10 s)	kW	50/45	45/37	46/38
Peak Regen Pulse Power (10 s)	kW	30	25	25
Max. Current -10s	A	300	300	300
Available Energy for CD Mode, 10-kW Rate	kWh	3.4	5.8	11.6
Available Energy for CS Mode, 10-kW Rate	kWh	0.5	0.3	0.3
Minimum Efficiency	%	90	90	90
Cold cranking power at -30°C	kW	7	7	7
CD Life	Cycle	5,000	5,000	5,000
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000	300,000
Calendar Life, 35°C	Year	15	15	15



Test Procedures Are Derived From Goals

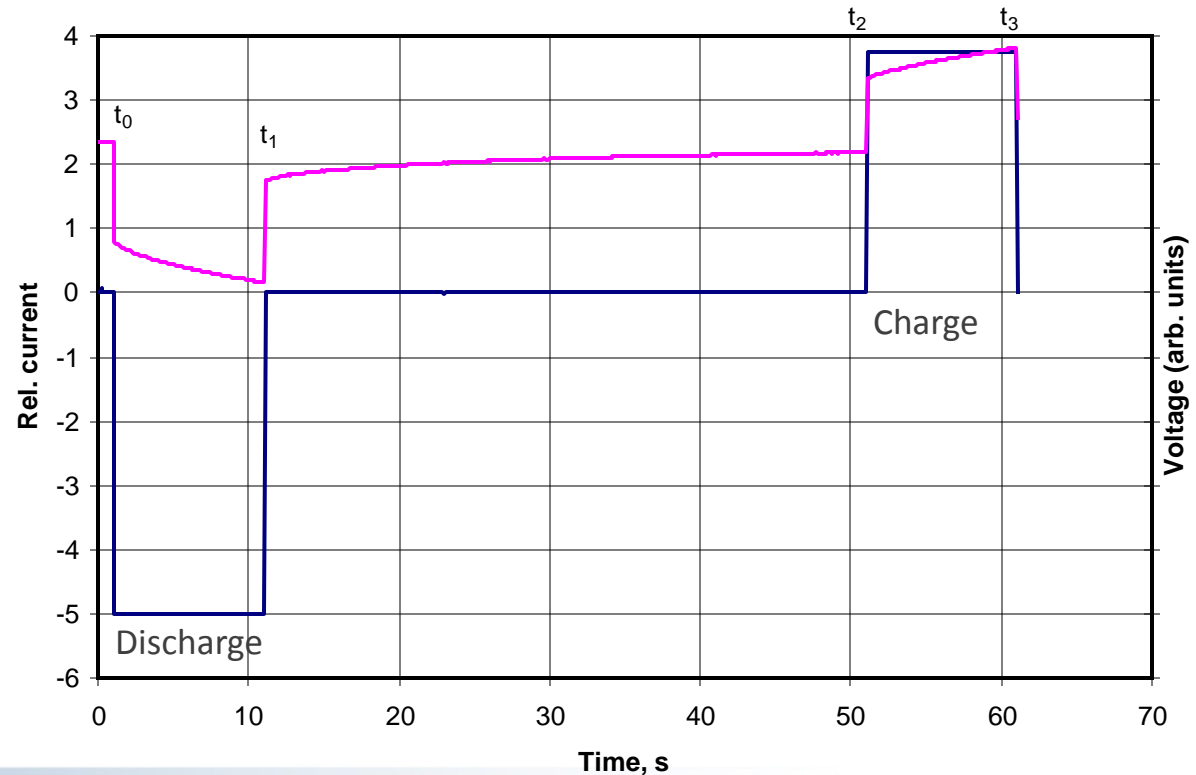
- The principle objective of the procedures in the test manual is to provide a means to compare battery performance and life to the targets
- For a PHEV, there are two modes of operation
 - Charge-depleting
 - Electric propulsion only
 - Discharges the battery
 - Charge-sustaining
 - Hybrid gasoline-electric propulsion
 - Maintains a relatively constant state-of-charge
 - Procedures allow the effect of each mode of operation on battery life to be characterized

Plug-in Hybrid Vehicle
Operation Modes



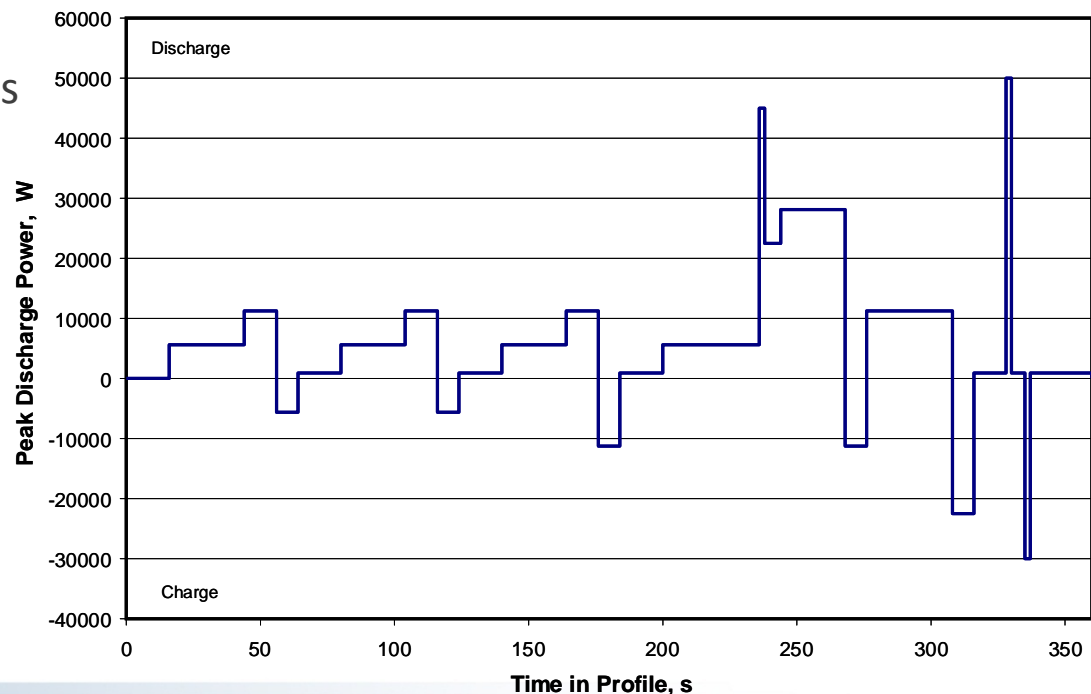
PHEV Test Procedures: Characterize Battery Performance

- Batteries are characterized in terms of constant-current capacity, self-discharge, hybrid pulse-power capability (HPPC), cold cranking (5 kW at -30°C), thermal performance and energy efficiency
- HPPC Test: Measure battery impedance and power/energy characteristics
- $R_d = \Delta V / \Delta I = (V_{t1} - V_{t0}) / (I_{t1} - I_{t0})$; $R_r = (V_{t3} - V_{t2}) / (I_{t3} - I_{t2})$
- End-of-test: Power or energy values are less than target values



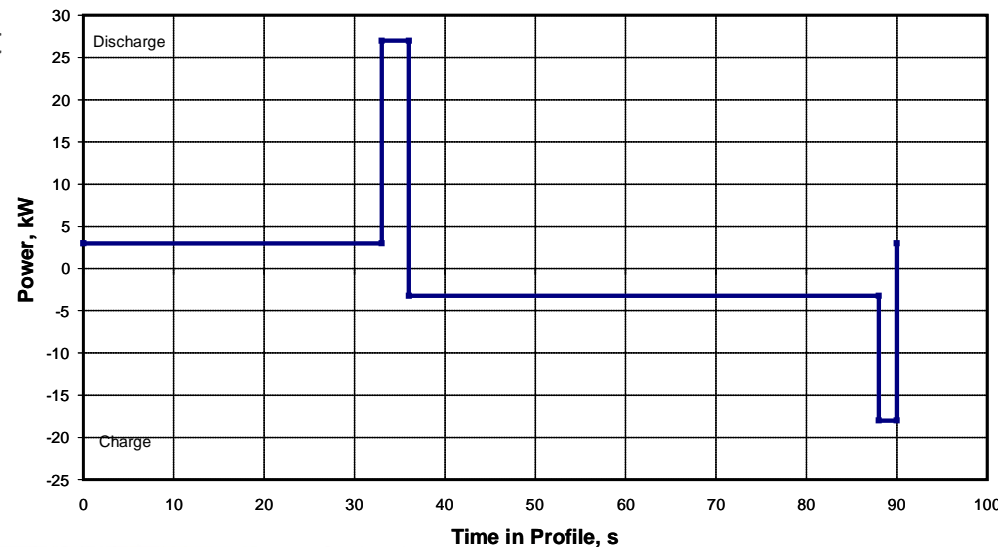
PHEV Test Procedures: Three Battery Life/Aging Tests (1)

- There are three battery life/aging tests: calendar, charge-depleting cycling and charge-sustaining cycling
- Calendar life: Similar to a storage experiment, where the battery is idle most of the time. A daily pulse is performed to gauge the health of the battery. These tests are performed at specific temperatures and a range of temperatures is typically used
- Charge-depleting (CD) cycling: Emulates electric propulsion in a prototypical vehicle. Starting from about 90% SOC, the cycle life profile is repeated until the scaled, goal CD energy is removed



PHEV Test Procedures: Three Battery Life/Aging Tests (2)

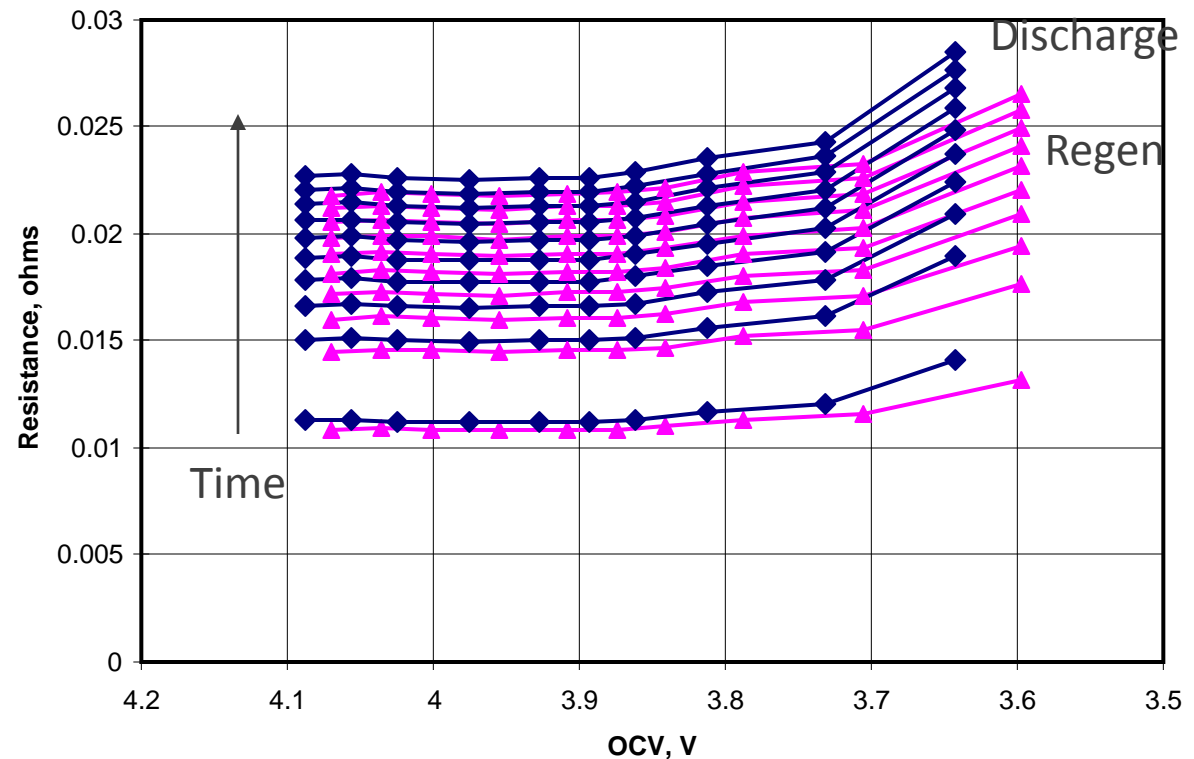
- Charge-sustaining (CS) cycling: Emulates the operation of a PHEV in hybrid electric vehicle mode. This profile is performed continuously and at low SOC
- CD and CS cycle profiles can be combined to better capture the operation of a PHEV
 - Perform CD profile to removed scaled amount of energy then perform 50 CS profiles
- Reference performance tests (RPTs) are performed every 32 days, 400 cycles and 30,000 cycles for calendar, CS cycle and CD cycle life, respectively
 - RPTs consist of constant-current capacity measurement and HPPC test at 30°C



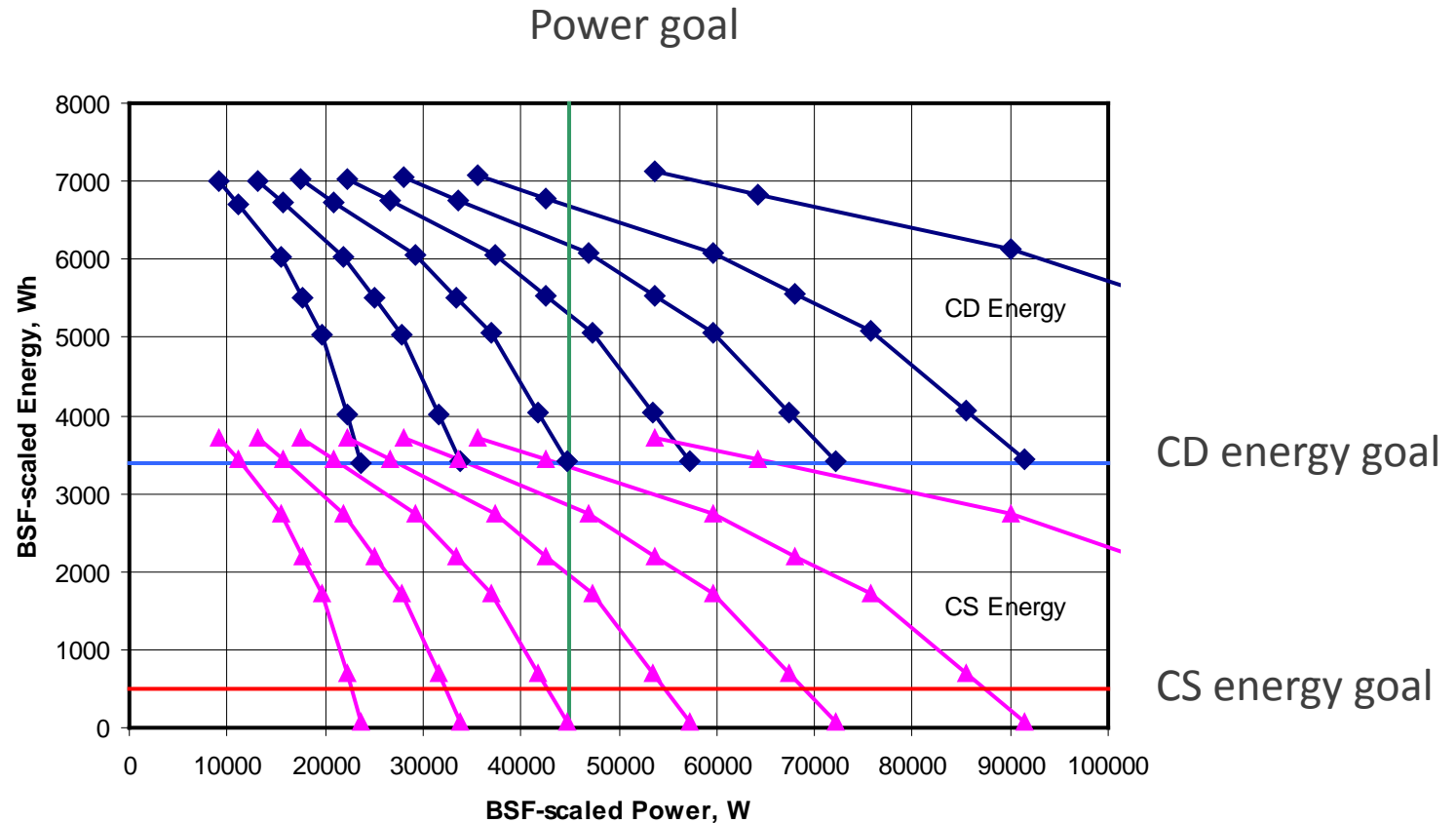
Example Results (Calculated)

- Hypothetic test: accelerated calendar life test at 30, 40, 50 and 60°C
- Reference performance tests every 4 weeks
 - Gauge capacity and resistance changes using capacity tests and HPPC
 - Calculate changes in power and energy abilities

- HPPC results with time

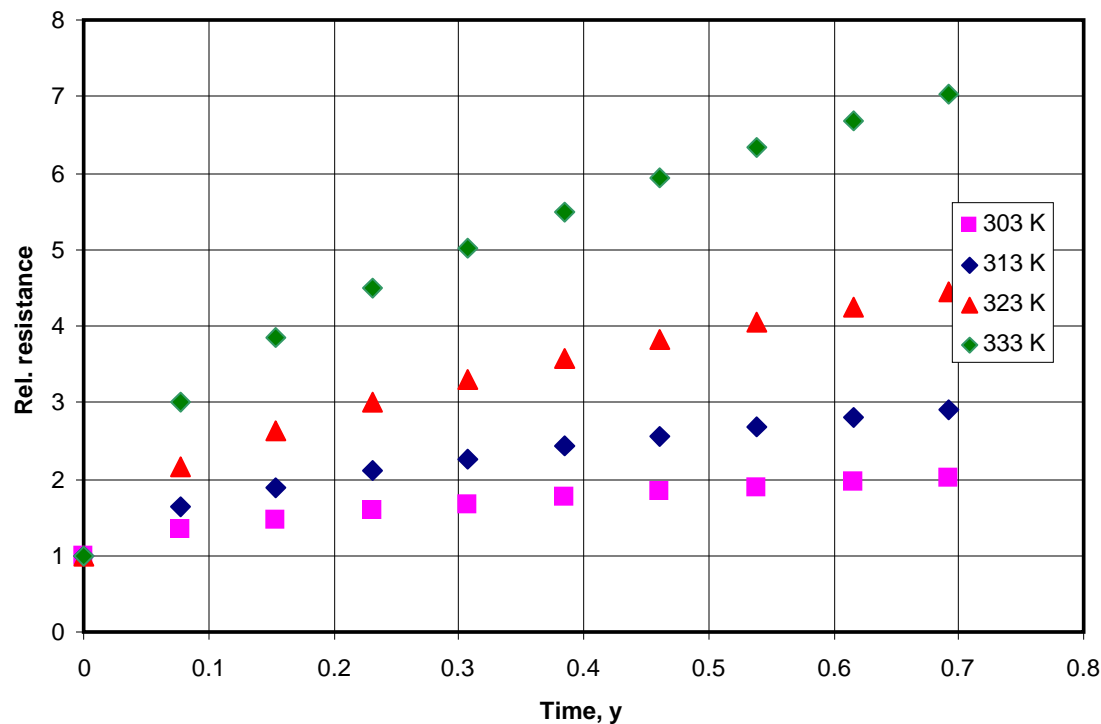


Energy and Power Ability Also Change with Time



Use Result to Model Changes

- Model can use any of the parameters of interest: capacity, CD/CS energy, power at either 3400 or 500 Wh, resistance
- Arrhenius plot using relative resistance as metric



- Estimate life using power fade
 - In example, battery reached EOL at RPT4 (20 weeks)



EV Battery Testing

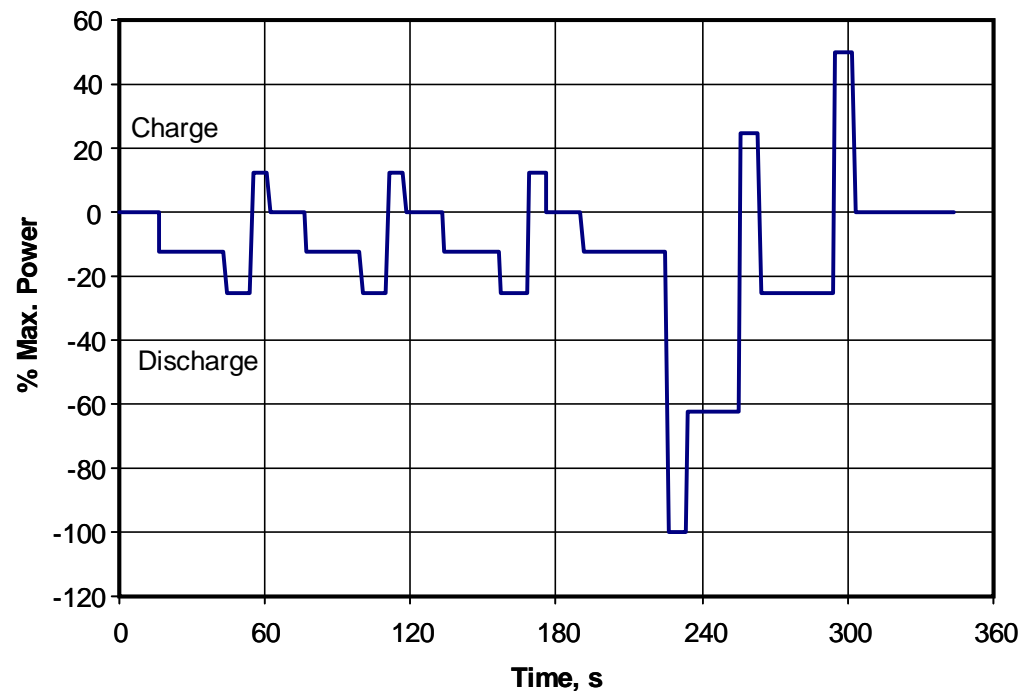
- The USABC has established performance and life targets for EVs
- Intended platform is a four-passenger, car which weighs about 1800-2000 kg and has a driving range of ~100 mi (160 km)
- Goals are based on battery weight and volume

Parameter	Target	
	Mid-Term	Long Term
Power density, W/L	460	600
Specific power (discharge; 80% DOD for 30 sec), W/kg	300	400
Specific power (regen; 20% DOD for 10 sec), W/kg	150	200
Energy density at C/3 rate, Wh/L	230	300
Specific energy at C/3 rate, Wh/kg	150	200
Specific Energy:Specific Power ratio	2:1	2:1
Total pack size, kWh	40	40
Life, years	10	10
Cycle life (80% DOD), cycles	1,000	1,000
Power and capacity degradation, % of rated	20	20
Operating environment	-40 to 50°C (20% performance loss; 10% desired)	-40 to 85°C
Normal recharge time, h	6	3 to 6
Fast recharge time	20-70% SOC in <30 min	40-80% SOC in 15 min



EV Test Procedures: Characterize Battery Performance(1)

- Batteries are characterized in terms of constant-current capacity (e.g., C/1, C/2 and C/3), dynamic stress test capacity, self-discharge, peak-power capability, thermal performance and energy efficiency

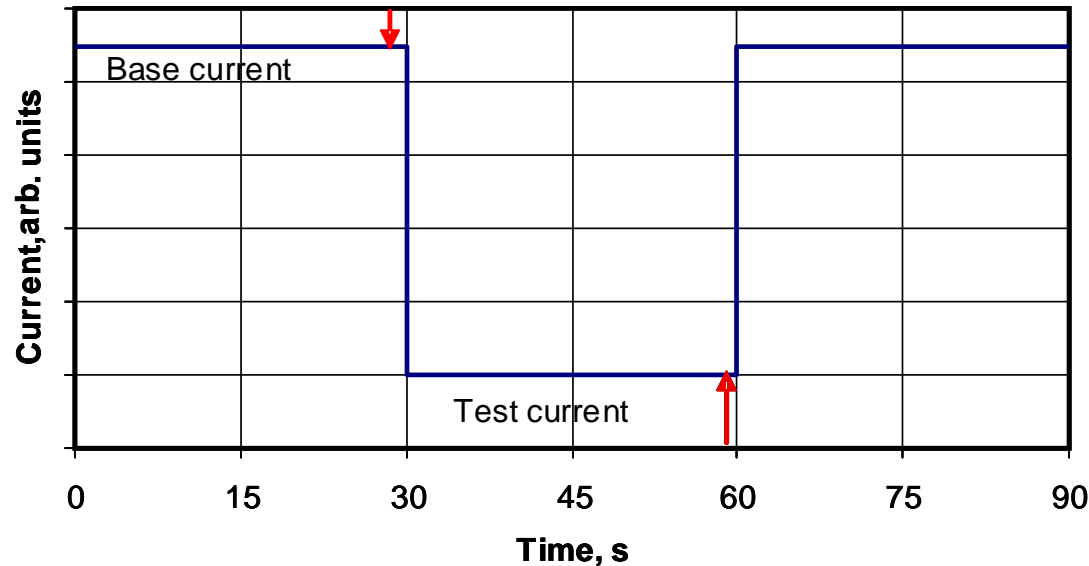


- Dynamic Stress Test Profile. The maximum discharge power peak is scaled to 80% of the peak power available at 80% depth of discharge.



EV Test Procedures: Characterize Battery Performance (2)

- Peak power test profile used to measure peak power at every 10%DOD



- The arrows indicate the points for measuring voltage (V) and current (I). From these points, $R = \Delta V / \Delta I$



EV Test Procedures: Characterize Battery Performance (3)

- Using the results from the peak-power test, the power capability at each %DOD is calculated using Equations (1), (2) and (3)

$$P_n = -\frac{2}{9} \frac{V_{IR-free}^2}{R} \quad (1)$$

$$P_n = -V_{lim} \frac{V_{IR-free} - V_{lim}}{R} \quad (2)$$

$$P_n = -I_{max} (V_{IR-free} + R \times I_{max}), \quad (3)$$

where P_n is peak power at n% DOD, $V_{iR-free}$ is the iR-corrected voltage at a given %DOD, R is resistance, V_{lim} is the limiting discharge voltage and I_{max} is the maximum current for the battery

- Report the minimum power value calculated

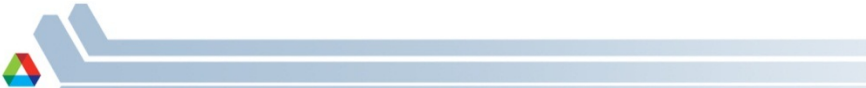
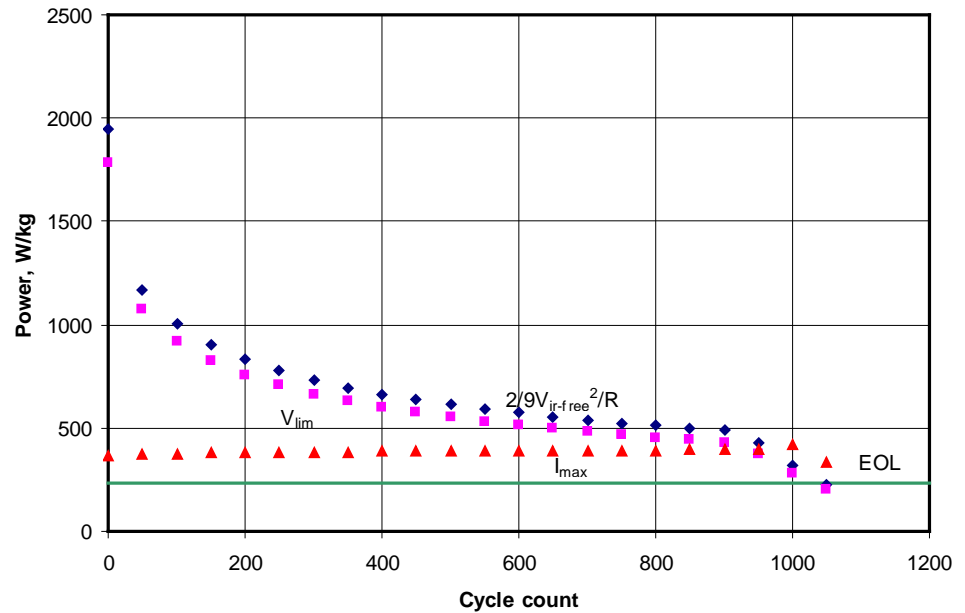
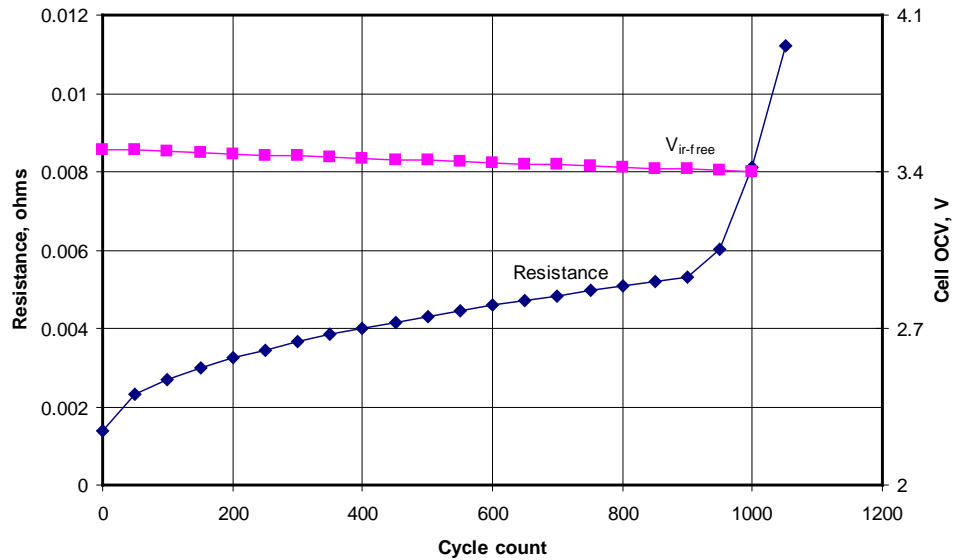


EV Test Procedures: Two Life/Aging Tests

- There are two life/aging tests, calendar life and cycle life
- Calendar life: This test is similar to a storage test and can be performed at many different %DOD and temperatures. Typically, it is performed at low %DOD and in the temperature range of 25 to 60°C. RPTs are performed every 28 days at 25°C
- Cycle life: This test uses the DST profile, scaled for the power characteristics and repeated many times, to discharge the battery from 0 to 80% DOD, followed by recharging it according to the developers recommendations. Increasing the temperature at which the battery is cycled will further increase the rate of performance decline. RPTs are conducted every 50 cycles at 25°C
- RPTs consist of C/3 constant-current capacity, DST-discharge capacity and the peak power test



EV Test Procedures: Calculated Results



Life Modeling Includes Stress Factors

- A simple life prediction model based on a single stress factor (e.g., temperature, T):
 - $Y(t, T) = 1 + \exp(b_0 + b_1/T) t^\rho + e$
 - where $Y(t, T)$ is the degradation parameter (e.g., resistance) at time (t) and temperature (T)
 - ρ is the power of time ($\rho = 0.5$ for typical ATD cells)
 - b_0 and b_1 are model parameters
 - e is the error term
- This model can be generalized to include multiple stress factors ($X_1 \dots X_n$):
 - $Y(t, X_1, X_2, \dots, X_n) = 1 + \exp(b_0 + b_1 X_1 + b_2 X_2 + \dots + b_n X_n) t^\rho + e$



Error Modeling

- The error model should include a combination of cell-to-cell effects (δ) and measurement error (ε):
 - $e = Var(Y(i, t)) = \sigma_{\delta}^2 (Y_{pop}(i, t) - 1)^2 + 2 \sigma_{\varepsilon}^2$
 - where $Var(Y(i, t))$ is the variance of Y at time t for the i^{th} experimental condition defined by the combined levels of the stress factors
 - σ_{δ}^2 is the variance of the cell-to-cell effects
 - σ_{ε}^2 is the measurement error variance
 - $Y_{pop}(i, t)$ is the value of Y at (i, t) predicted by the life model



Apply Methodology to Cell Test Data*

- A model was applied to a set of cells that were calendar-life aged at various temperatures (an isothermal experiment)
- The 30°C data were not used to construct the model

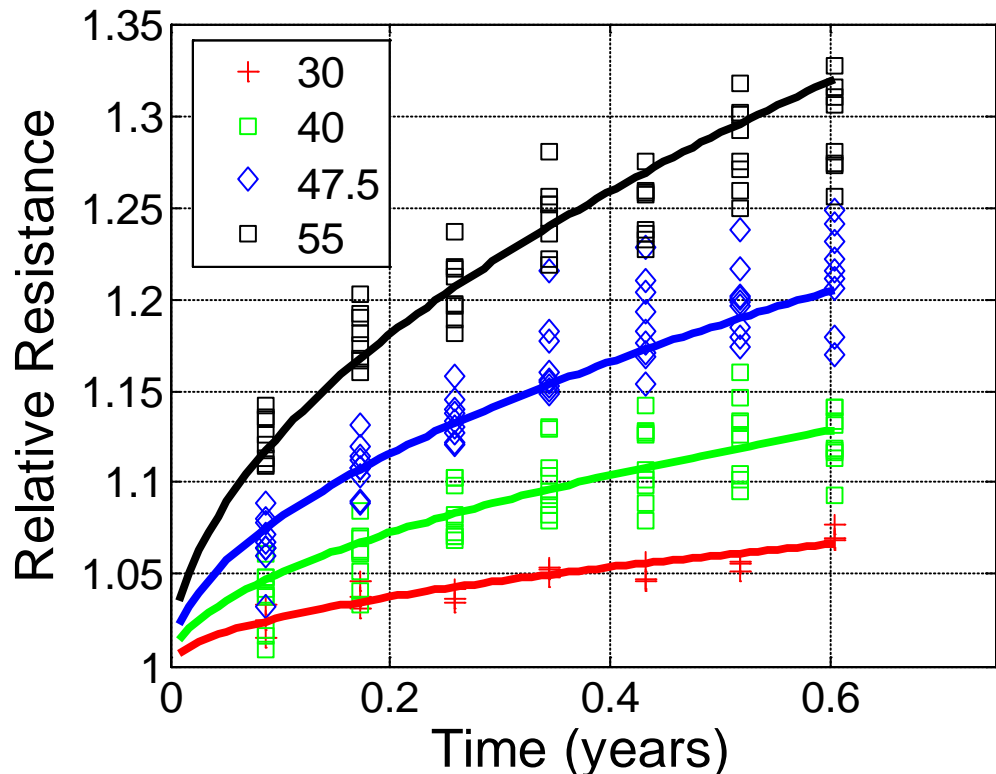
$$\hat{Y} = 1 + \exp\left\{\hat{\beta}_0 + \hat{\beta}_1 \cdot \frac{1}{T}\right\} \cdot t^{0.5}$$

t = time (years)

T = temperature (K)

$$\hat{\beta}_0 = 18.11$$

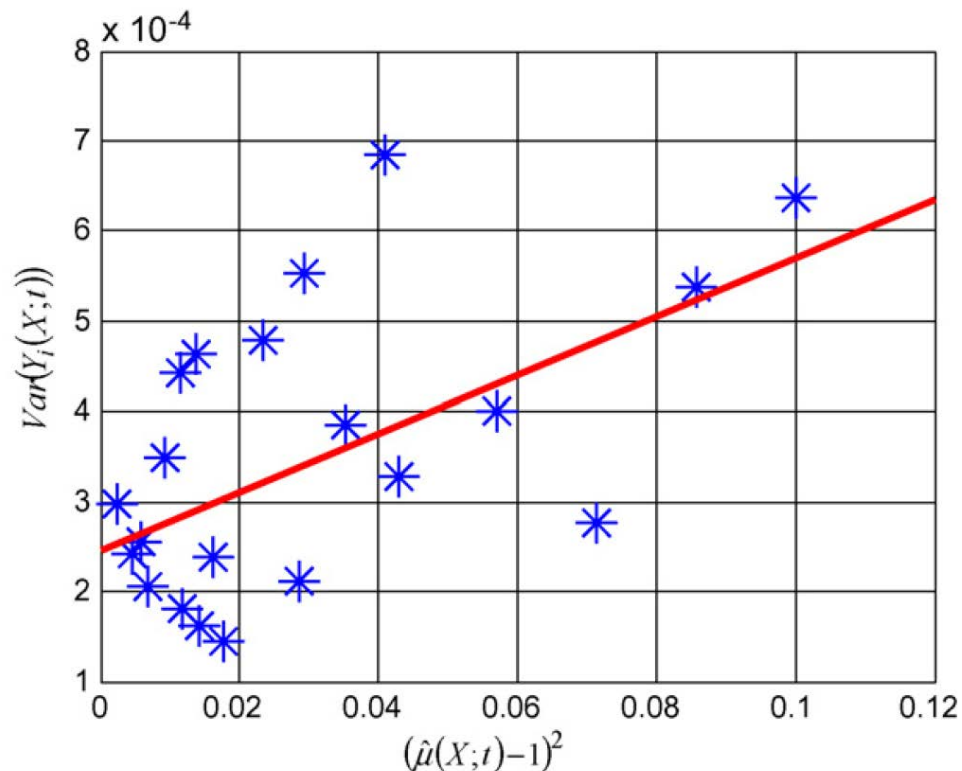
$$\hat{\beta}_1 = -6236$$



* E.V. Thomas, I. Bloom, J.P. Christophersen, V.S. Battaglia, *J. Power Sources*, 184 (2008) 312–317

Apply Methodology to Cell Test Data - Error Estimation

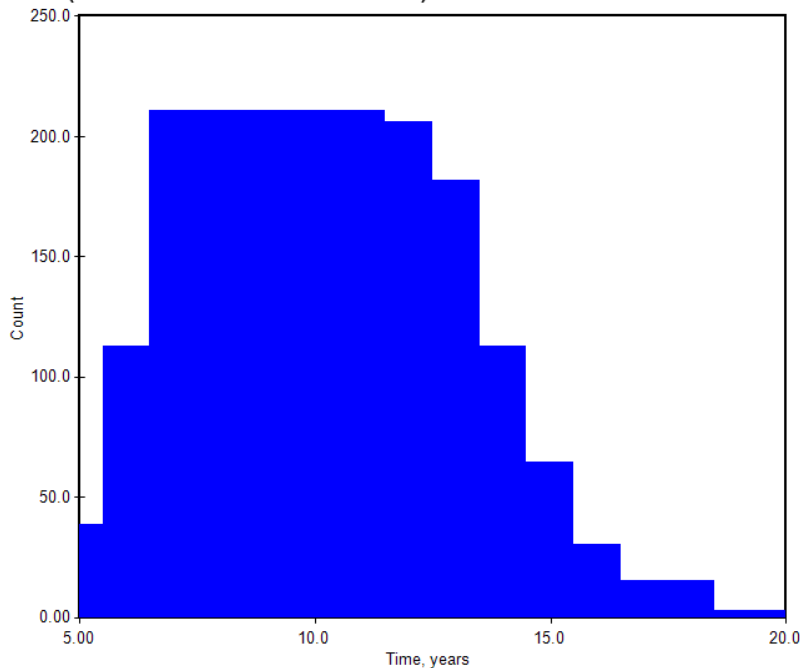
- The fitted error model shows the sample variance of observed relative resistance versus the square of the difference between the expected relative resistance and unity.
- The estimated error model parameters are given by the slope and half of the intercept of the fitted line.
 - $\hat{\sigma}_\delta^2 = 3.2 \times 10^{-3}$
 - $\hat{\sigma}_\varepsilon^2 = 1.2 \times 10^{-4}$



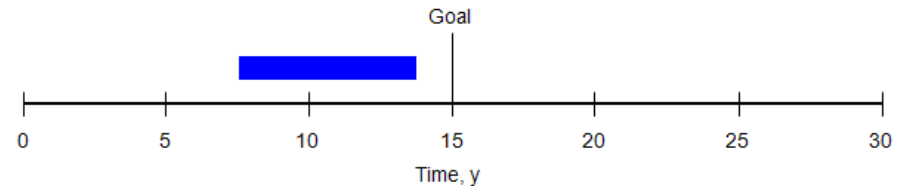
Estimate Battery Life Within a Confidence Interval

- Use results of curve fitting and error estimation in Monte Carlo simulations (a probabilistic approach)
- Life estimation was completed with 1000 Monte Carlo simulations
- The estimated life for these cells is in the range of 7.6 and 13.8 years
 - Estimated life does not meet USABC Goal of 15 years

Monte Carlo simulations
(1000 simulations)



Life estimate at 95% LCL= 7.6 y
Life estimate at 95% UCL= 13.8 y



Summary

- Pre-competitive battery testing in the US is application-based and, thus, has many targets and procedures
- The test procedures can be used on any size cell, module or battery and on battery technologies at different levels of maturity
- The results of testing provide a guide to actual battery performance in the vehicle
- A statistically-valid modeling methodology has been illustrated

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